

# THE VENUS FLAGSHIP STUDY: ATMOSPHERIC SCIENCE FROM TWO DESCENT/LANDING VEHICLES AND TWO BALLOONS

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and  
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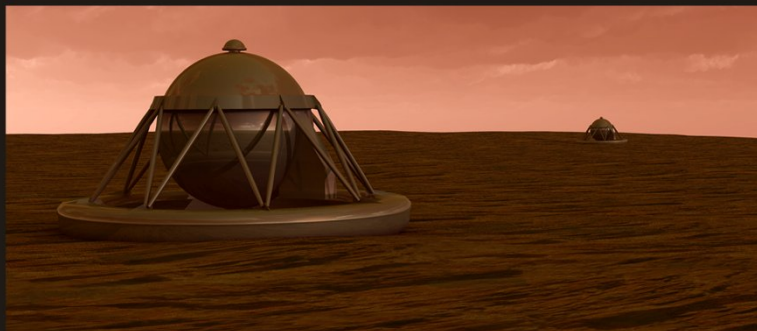
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# NASA's Flagship Mission to Venus

April 6, 2009



Venus Science & Technology Definition Team

Final Report of the

One year study

Report released 6 April 2009

Team consisted of atmospheric scientists, planetary geologists, planetary geophysicists, mission designers, technology experts, and engineers

Important architecture and costing support by JPL's Team X

Beautiful web site!

<http://vfm.jpl.nasa.gov/>

# Venus STDT Objectives

- **Phase 1:** Develop and Prioritize Science Objectives and Investigations for a Venus flagship mission drawing upon
  - VEXAG White Paper (2007)
  - NRC Decadal Survey (2003) and NOSSE update (2008)
  - NASA's SSE Roadmap (2006)
- **Phase 1:** Identify the optimal architecture to achieve science objectives
- **Phase 2:** Execute the Design Reference Mission design from a science-driven architecture trade
  - Design and assess scientific performance of payload
  - Assess Performance, Cost, Risk, and Technology Readiness
- **Phase 2:** Identify Technology Development
  - To fully execute the Design Reference Mission
  - For alternate payloads and architectures

# International Collaboration

- Multi-element architecture lends itself to international collaboration
- Timing for international collaboration:
  - NASA (Venus Flagship)
  - ESA (VEX Current-2011)
  - ESA (Cosmic Vision EVE > 2020)
  - JAXA (VCO 2010)
  - Russia (Venera D 2016)



# Venus Flagship Mission Assumptions & Constraints

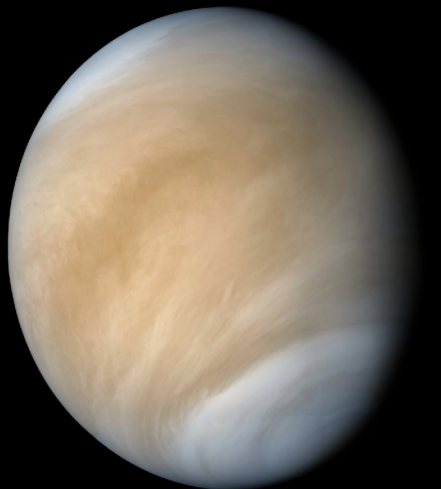
- Launch Opportunity: 2020 to 2025
- Technology Maturation: TRL 6 by 2015
- Life Cycle Mission Cost Range: \$3 - 4B (FY '08)
- LV Capability:  $\leq$  Delta IVH equiv.
- DSN Capability: up to 34M, Ka band
- International Contribution: No foreign cost contribution
- Assume no earlier missions prior to flight of the Venus Flagship Mission

# Why is Venus so different from Earth?

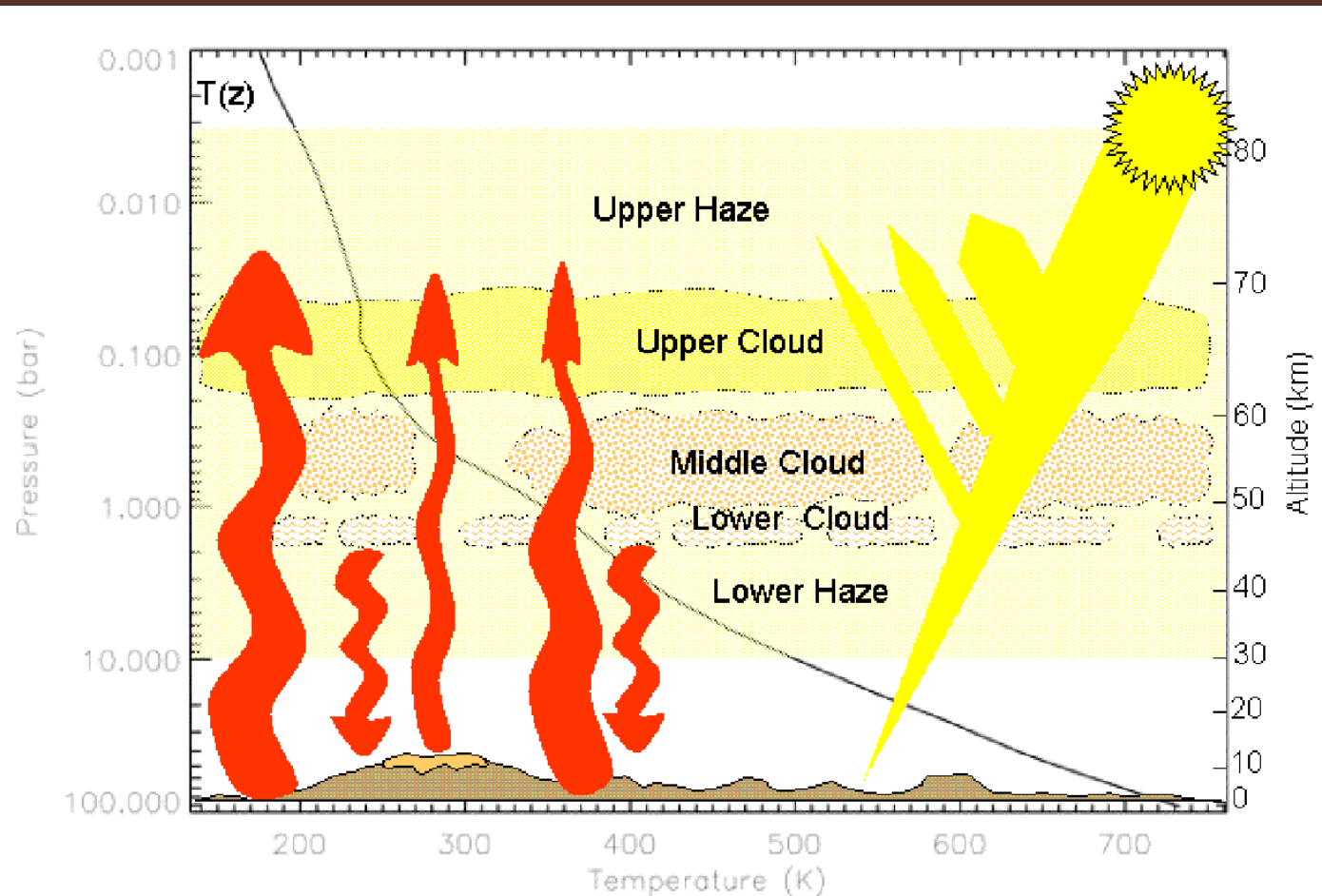
- What does the Venus greenhouse tell us about climate change?
  - How do clouds and chemical cycles affect atmospheric energy balance?
  - What drives the atmospheric superrotation?
  - Is there evidence for climate change?
- How active is Venus?
  - Is Venus geologically active and what is its geologic history?
  - How do surface/atmosphere interactions affect rock mineralogy and climate?
  - What is structure of the interior, and what are its dynamics?
- When and where did the water go?
  - How did the early atmosphere evolve?
  - Did Venus have an ocean and if so, when was it lost?
  - Is there continent-like crust on Venus?

# The Venus Greenhouse

How does the greenhouse work, and has Venus experienced climate changes?

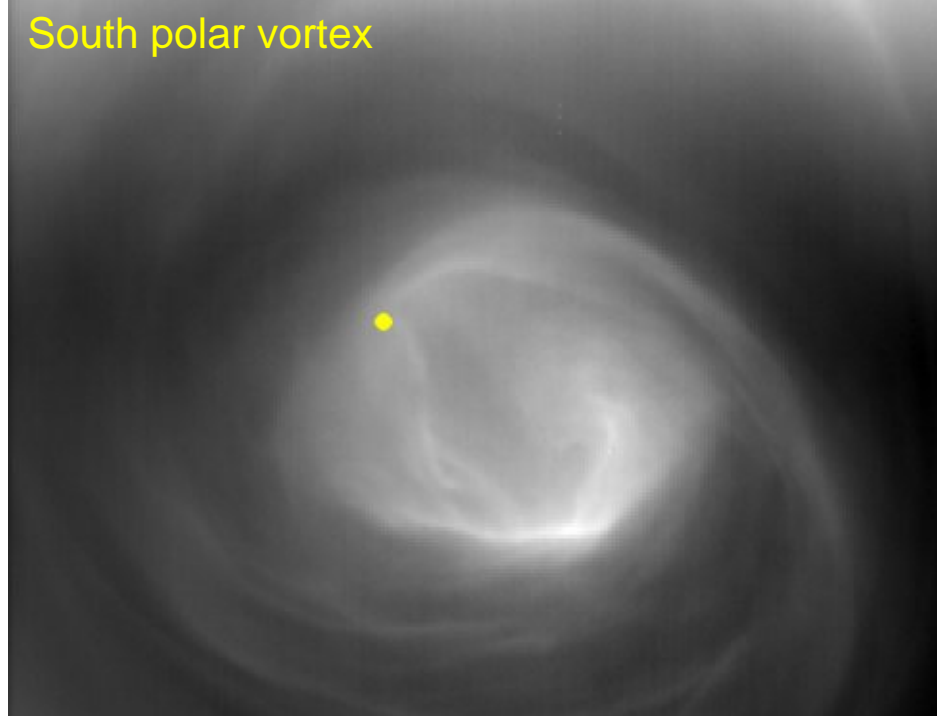


Mariner 10



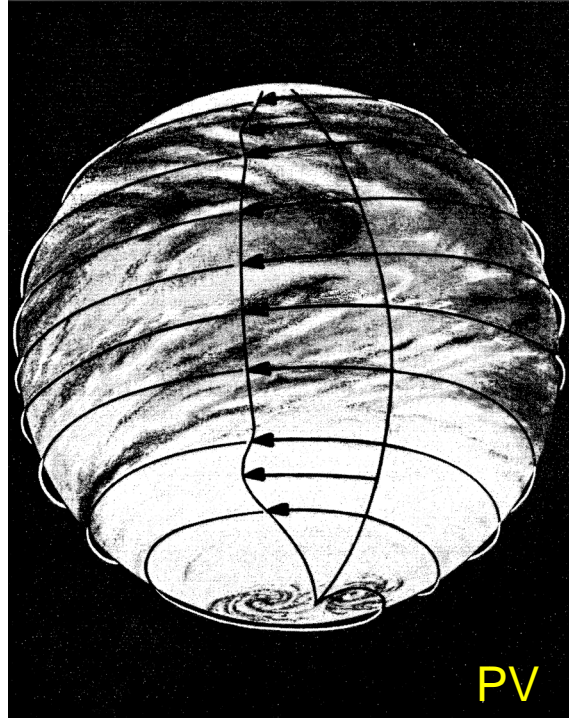


South polar vortex



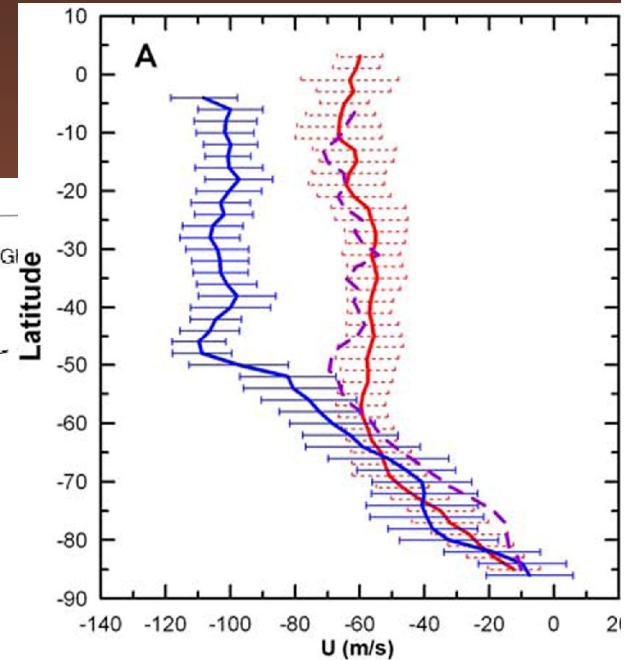
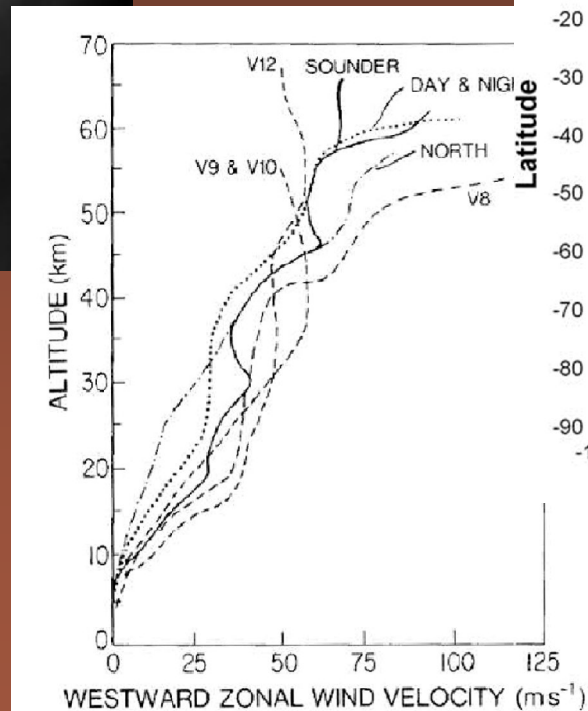
Why does the atmosphere superrotate?

Probes: Winds decrease with altitude



VEX

PV



VEX East-west winds, decreasing at the poles



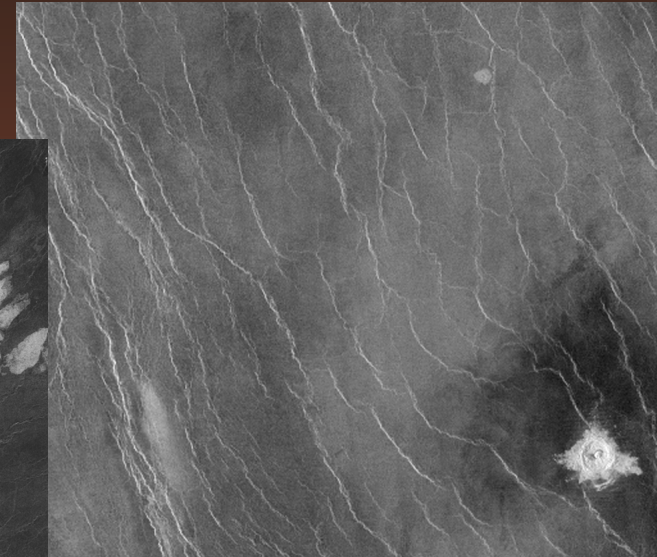
# Is Venus Geologically Active?

Magellan saw  
young volcanic  
features

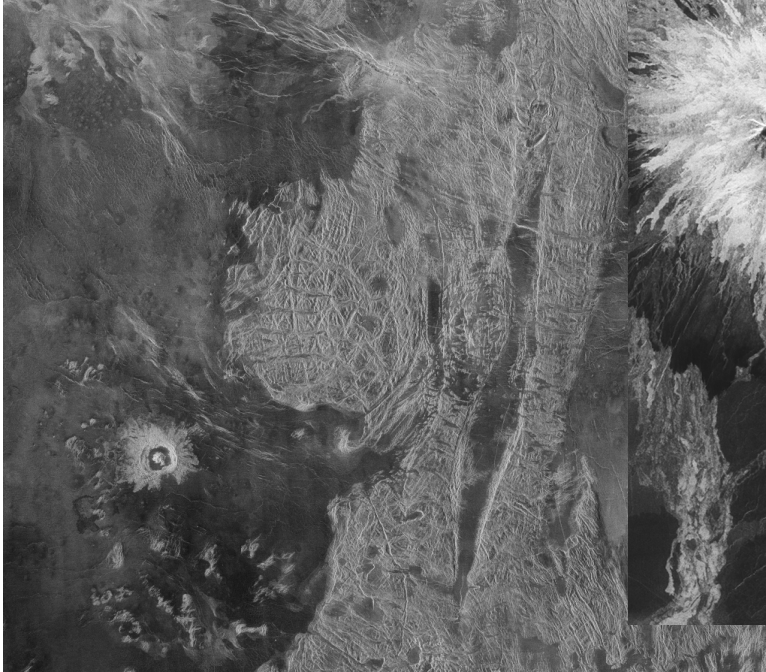
*Volcanoes*



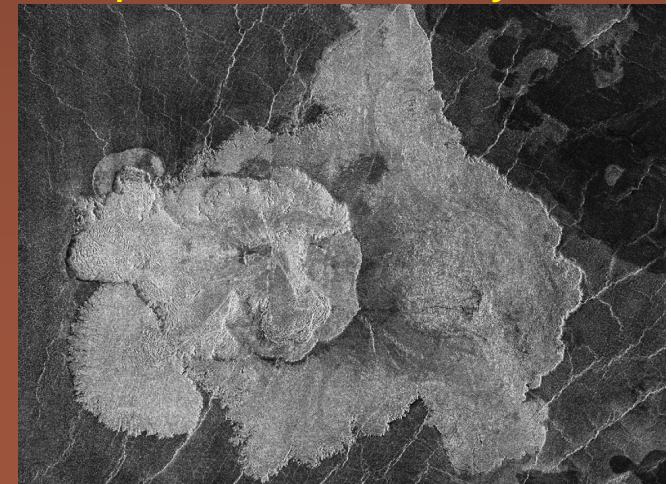
*Plains*



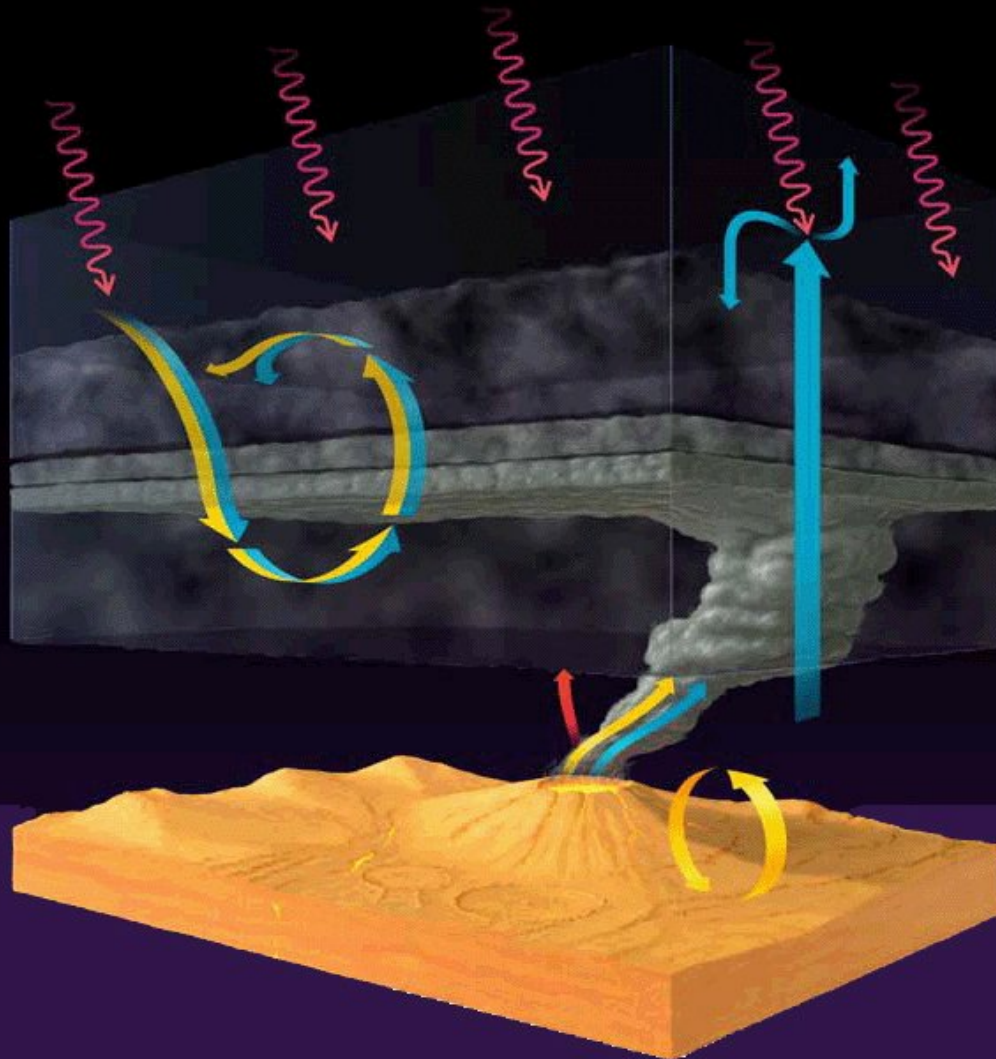
*Tessera*



*Compositional Diversity*



# How did early Venus evolve? Did it have oceans?



High D/H means  
Venus once had much  
more water.

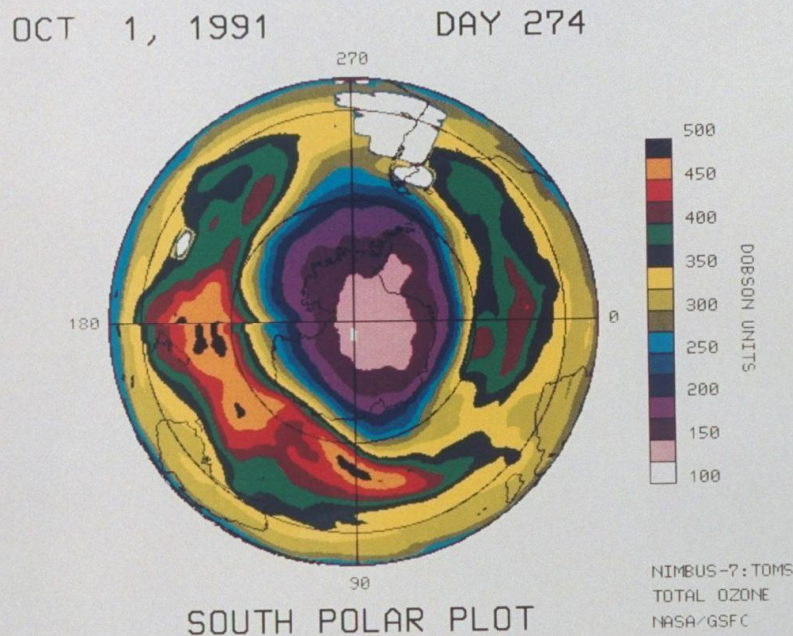
Venus' climate is an  
interconnected system  
of atmospheric,  
geologic, and surface  
chemistry processes,  
just like the Earth's.

Was Venus once  
habitable?



# Learning about Earth by Studying Venus

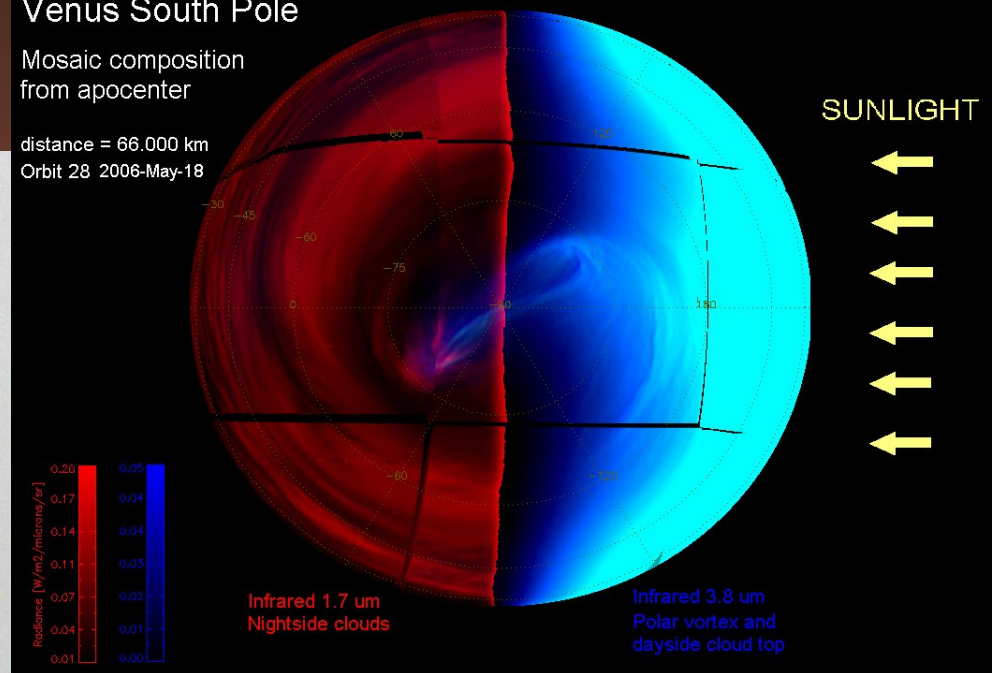
Prediction of O<sub>3</sub> loss due to CFCs followed directly from studying Venus atmospheric chemistry. TOMS below (Earth)



## Venus South Pole

Mosaic composition  
from apocenter

distance = 66,000 km  
Orbit 28 2006-May-18



South polar vortex of Venus exhibits instability and ways to test Earth atmosphere dynamics VEX (left IR emission, right solar reflection)

# Venus Flagship Science Objectives

| Science Theme  | Science Objective   |
|--|---|
| What does the Venus greenhouse tell us about climate change? | Understand radiation balance in the atmosphere and the cloud and chemical cycles that affect it |
|  | Understand how superrotation and the general circulation work                                   |
|  | Look for evidence of climate change at the surface  |
| How active is Venus?   | Identify evidence of current geologic activity and understand the geologic history              |
|  | Understand how surface/atmosphere interactions affect rock chemistry and climate                |
|  | Place constraints on the structure and dynamics of the interior                                 |
| When and where did the water go?                             | Determine how the early atmosphere evolved  |
|  | Identify chemical and isotopic signs of a past ocean  |
|  | Understand crustal composition differences and look for evidence of continent-like crust        |

Main resources:

- 2003 Decadal Survey
- VEXAG 2007 report
- 2006 NASA Roadmap

# Mission Architecture Trade Study

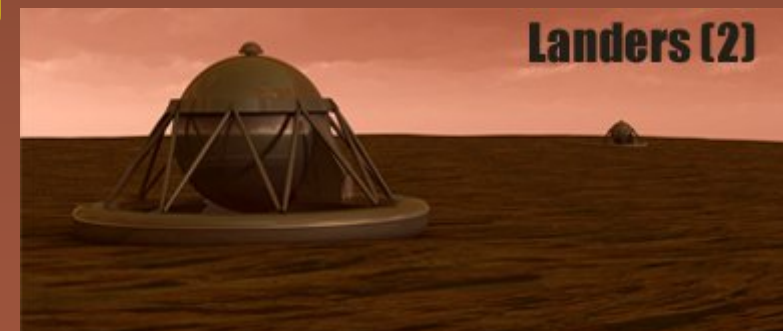
- STDT & JPL Team assessed the mission architecture trade space:
  - Identified 13 architectural elements
    - e.g. orbiter, landers, balloons, probes
  - Targeting various altitude regimes
    - from surface to low/mid/high altitudes and orbit
  - Single and multiple elements were considered
    - e.g., networks, multi-probes
- These architecture elements assembled into 17 mission architectures
- Science FOMs and Technology Difficulty used to select highest value science architecture within design constraints

*Magellan - Ishtar Terra*



# Design Reference Mission

- The DRM requires a dual-launch approach using a pair of Atlas V 551s
  - 1 orbiter, arrives first to serve as telecom relay
  - 1 carrier, arrives second, with 2 entry vehicles, each with a balloon and a lander, delivered into the atmosphere 13 hours apart
  - Launches in 2021, arrivals in 2022
  - Orbiter serves as a telecom relay for landers (5 hours) and balloons (30 days)
  - 2 year radar mapping science mission after aerobraking to a 230 km circular orbit
- The balloons and landers communicate through the orbiter, with the carrier serving as a limited emergency backup
- The lander sites are Alpha Regio ( $-27^{\circ}$ ,  $3^{\circ}$  E) and the lava flows at  $-47.4^{\circ}$ ,  $6.5^{\circ}$  E
  - The balloons are expected to circumnavigate Venus 5-7 times and drift poleward

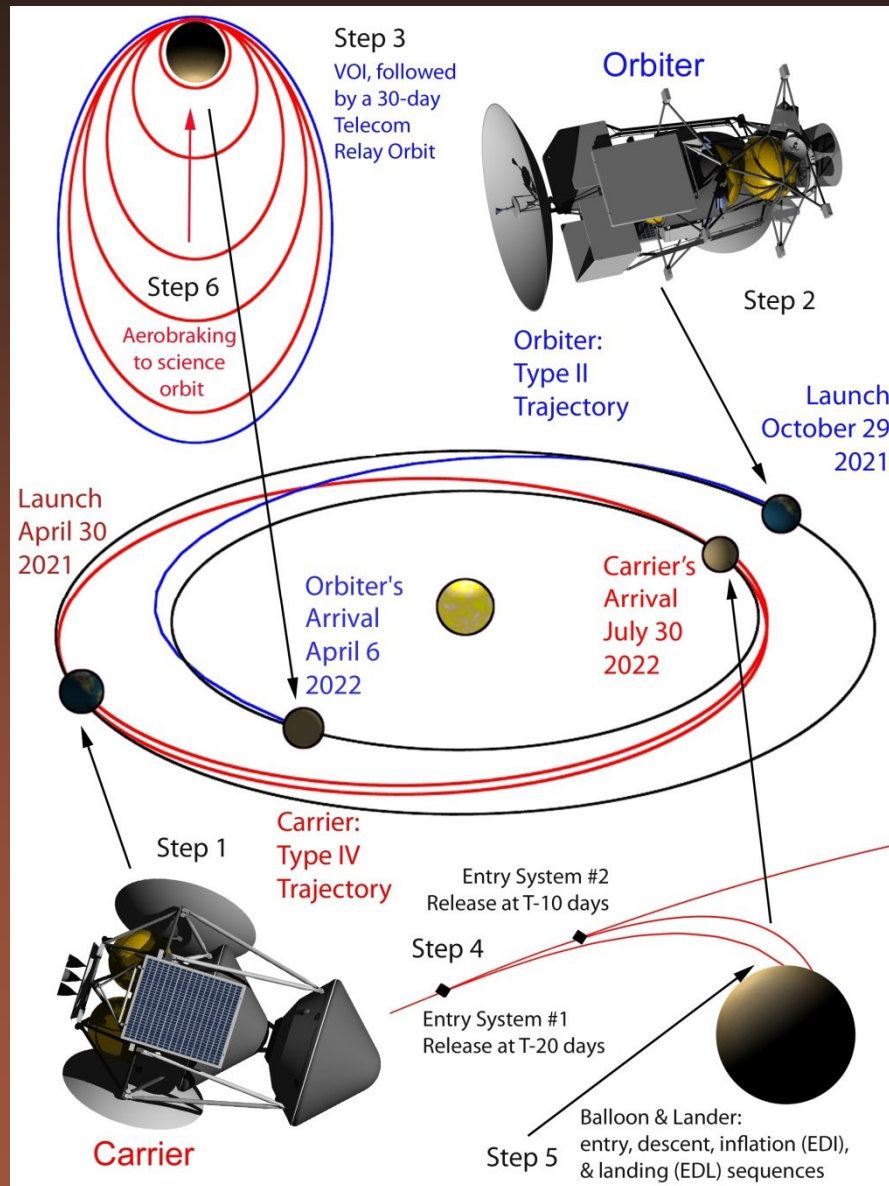




# DRM Planning Payload

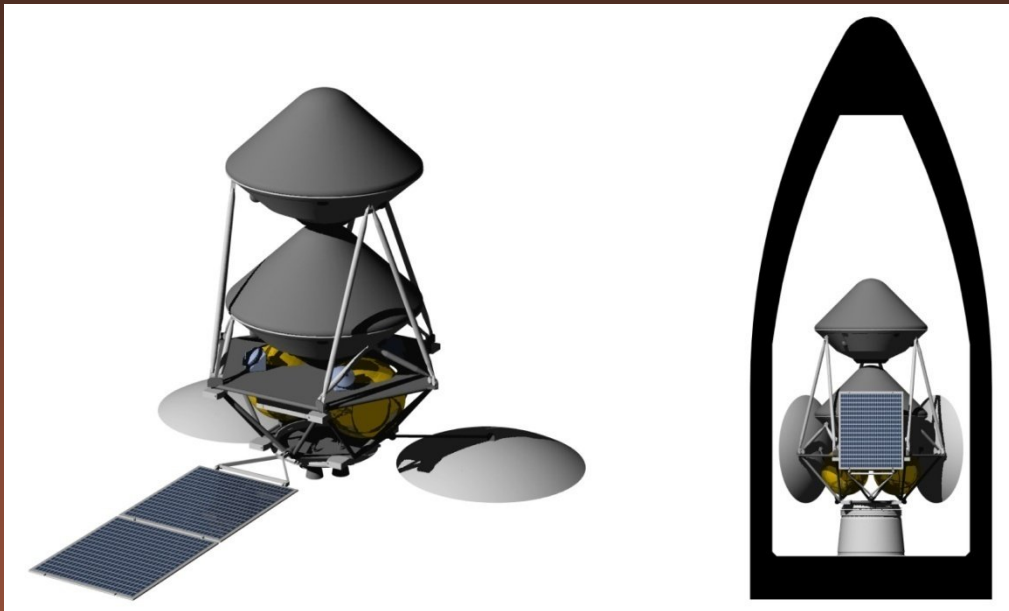
| Orbiter   | 2 Balloons   | 2 Landers                                    |  |
|---|--|--|--|
| Lifetime (4 years)                                  | (1 month)  | Descent Phase<br>(1–1.5 hour)                | Landed Phase<br>(5 hours)                        |
| InSAR — Interferometric<br>Synthetic Aperture Radar | ASI — Atmospheric<br>Science Instrument<br>(pressure, temperature,<br>wind speed,) | ASI  | Microscopic imager                               |
| Vis–NIR Imaging<br>Spectrometer                     | GC/MS — Gas<br>Chromatograph /<br>Mass Spectrometer                                | Vis–NIR Cameras<br>with spot<br>spectrometry | XRD / XRF  |
| Neutral Ion Mass<br>Spectrometer                    | Nephelometer   | GC / MS                                      | Heat Flux Plate                                  |
| Sub–mm Sounder                                      | Vis-NIR camera   | Magnetometer                                 | Passive Gamma Ray<br>Detector                    |
| Magnetometer  | Magnetometer   | Net Flux<br>Radiometer                       | Sample acquisition,<br>transfer, and preparation |
| Langmuir Probe                                      | Radio tracking   | Nephelometer                                 | Drill to ~10 cm                                  |
| Radio Subsystem (USO<br>— Ultra Stable Oscillator)  |  |  | Microwave corner<br>reflector                    |

# Mission Design



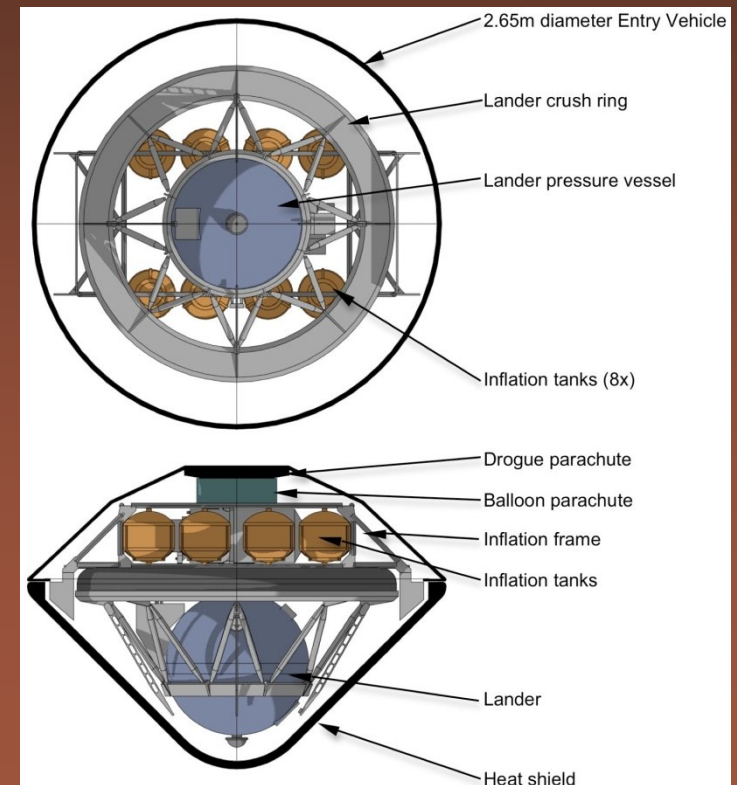
- Carrier with entry vehicles launches first, arrives second
- Orbiter launches second, arrives first and sets up to be a telecom relay in a 300 x 40000 km near polar orbit
- Entry vehicles arrive 13 hours apart so only 1 lander communicates with the orbiter at a time
- After 1 month of balloon mission, orbiter ends telecom support and aerobrakes down to a 230 km circular orbit for a 2 year science mission phase

# Carrier and Entry Vehicles

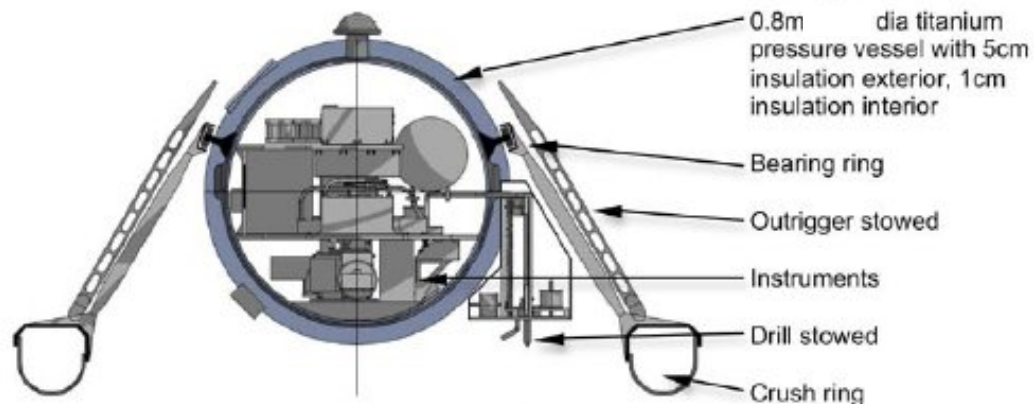


The carrier uses an inline stacked configuration for the entry vehicles. There is ample room inside the 4.5 m launch vehicle fairing.

The entry vehicles are PV and Galileo style 45° sphere cone aeroshells, sized at 2.65 m diameter to accommodate all internal components.



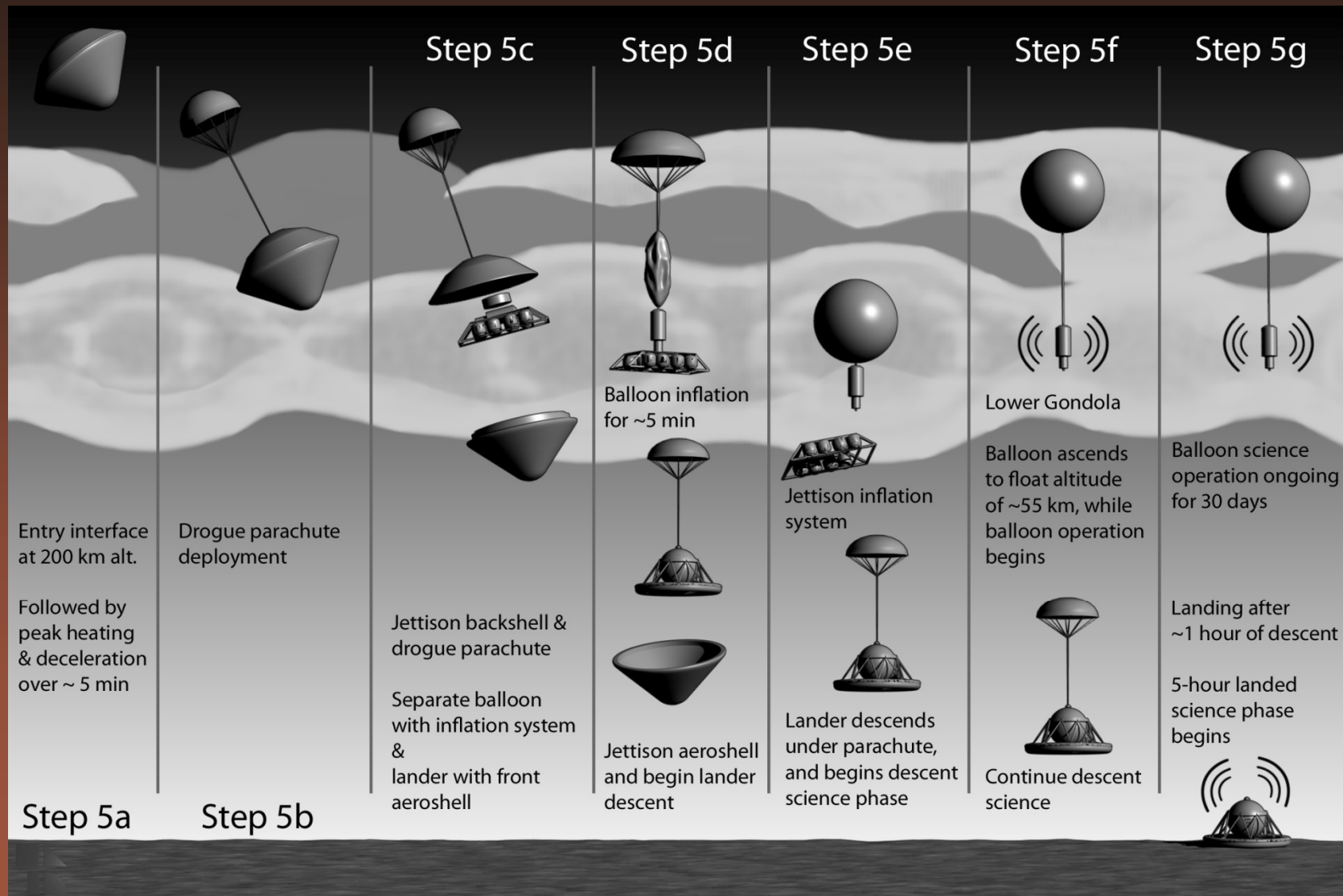
# Landers and Balloons



5.5 m prototype superpressure balloon  
(JPL/ILC Dover/NASA Wallops)



# Entry, Descent and Landing (Inflation)



# Launch Mass Summary

- Each of the two launch vehicles in our architecture needed to be the largest Atlas V available (Atlas 551):
- Orbiter:
  - Dry Mass (CBE) = 1591 kg
  - Margin (43%) = 684 kg
  - Propellant = 3030 kg
  - Total = 5305 kg
  - LV capability = 5450 kg
  - LV Margin = 2.6%
- Carrier & In situ vehicles:
  - Carrier (CBE) = 781 kg
  - Entry Vehicles (2) CBE = 1566 kg
  - Landers (2) CBE = 962 kg
  - Balloons (2) CBE = 209 kg
  - Helium CBE = 26 kg
  - Margin (43%) = 1511 kg
  - Propellant = 523 kg
  - Total = 5578 kg
  - LV capability = 5580 kg
  - LV Margin = 0%





# Data Volume Summary

- Preliminary data collection budgets were developed for all of the instruments on all of the platforms.
  - Orbiter (300 Tbits):
    - InSAR instrument provides ~99.99% of all orbiter data
  - Lander (1 Gbit each):
    - Panoramic imaging: 590 Mbits (59%)
    - Descent imaging: 200 Mbits (20%)
    - XRD/XRF: 140 Mbits (14%)
  - Balloon (21 Mbit each):
    - VASI + nephelometer: 18 Mbits (86%)
    - GCMS: 1.6 Mbits (8%)
    - Microphone 0.7 Mbits (3%)
- The data collection strategy is different for each platform:
  - Orbiter data is collected throughout the 2 year main science mission
  - Lander data is collected continuously during the 1 hour descent and 5 hour surface mission.
  - Balloon data is collected over 30 days, with significant duty-cycling to conserve electrical power.

# Primary Issues and Risks

- Sample acquisition and handling
  - Venera/VEGA heritage is dated, improved capabilities likely will be required.
- Lander design and technologies
  - Require design for safe landing on rough terrain (tessera). Rotating pressure vessel concept requires development and validation.
- Launch vehicle limits
  - Atlas 551 limit already reached with 43% margin on CBE. Further mass growth will require descopes or much more expensive launch vehicles.
- Orbiter failure risk
  - Carrier can provide only a limited backup telecom capability if the orbiter fails.
- System engineering complexity
  - The multi-element architecture is complex and few system engineering details have been worked out so far.
- Cost estimation uncertainties
  - Lack of experience and existing facilities makes it difficult to estimate costs for high temperature and high pressure V&V of lander and exposed instruments.

# DRM Cost Estimates

- The JPL cost-complexity model (Peterson et al, 2008) gave a \$2.7B estimate for the Design Reference Mission
  - The stated accuracy of this model ~40% on absolute cost, implying a maximum possible cost of \$3.8B.
- The JPL study team created a second cost estimate that fused three sources: JPL's Team X cost models, study team expert inputs and a cost risk subfactor analysis to determine a recommended reserve level. The result is:

| Element                                 | Cost        |
|---|-------------|
|   | (\$M)       |
| Spacecraft CBE from Team X              | 1954        |
| Additional PSE costs                    | 30          |
| Cost Reserves on CBE (41% )             | 813         |
| Two Atlas 551 launch vehicles           | 445         |
| Additional Technology Development Costs | 107         |
| <b>Total</b>                            | <b>3349</b> |

- This cost is \$3.35B, which is within the uncertainty range of the cost-complexity model.
- The final report lists a cost range of \$2.7B to \$3.8B for the DRM

# Technology Priorities

## Technologies for DRM

|   |   |
|---|---|
| 1 | Surface sample acquisition system and handling at Venus surface                   |
| 2 | Lander technologies for rotating pressure vessel and rugged terrain survivability |
| 3 | Venus-like environmental test chamber   |

## New capabilities

|   |   |
|---|---|
| 4 | Refrigeration for the Venus surface environment                     |
| 5 | High temperature sensors and electronics, including telecom systems |

## Enhancement to current DRM design

|   |   |
|---|---|
| 6 | Extension of lander life through advanced thermal control |
|---|---|

# DRM Science Traceability- Themes to Observation Platforms

| Science Theme  | Science Objective   | Instrument Type  | Observation Platform             |
|--|---|--|----------------------------------|
| What does the Venus greenhouse tell us about climate change? | Understand radiation balance in the atmosphere and the cloud and chemical cycles that affect it   | Vis-NIR Imaging Spectrometer                           | Orbiter                          |
|  |   | Nephelometer   | Balloon plus Lander (on descent) |
|  |   | Net Flux Radiometer                                    | Lander (on descent)              |
|  | Understand how superrotation and the general circulation work   | Sub-millimeter Sounder                                 | Orbiter                          |
|  |   | Atmospheric Structure (P/T/winds/accel)                | Balloon plus Lander (on descent) |
|  |   | Radio (with USO)                                       | Balloon                          |
|  | Look for evidence of climate change at the surface  | Vis-NIR Camera   | Balloon plus Lander (on descent) |
|  |   | Microscopic Imager                                     | Lander                           |
| How active is Venus?   | Identify evidence of current geologic activity and understand the geologic history  | InSAR  | Orbiter                          |
|  | Understand how surface/atmosphere interactions affect rock chemistry and climate<br>Place constraints on the structure and dynamics of the interior | GC/MS  | Lander (on descent)              |
|  |   | Radio (with USO)                                       | Orbiter                          |
|  |   | Magnetometer   | Orbiter, Balloon, Lander         |
|  |   | Heat Flux Plate  | Lander                           |
|  |   | Corner Reflector                                       | Lander                           |
| When and where did the water go?                             | Determine how the early atmosphere evolved  | GC/MS  | Balloon plus Lander (on descent) |
|  |   | Langmuir Probe   | Orbiter                          |
|  |   | Neutral and Ion Mass Spectrometer (INMS)               | Orbiter                          |
|  | Identify chemical and isotopic signs of a past ocean  | XRD/XRF  | Lander                           |
|  |   | Drill and sample acquisition, transfer and preparation | Lander                           |
|  | Understand crustal composition differences and look for evidence of continent-like crust  | Passive Gamma-ray Detector                             | Lander                           |

# Open Science Questions

## The Atmosphere

| MAJOR OPEN SCIENTIFIC QUESTIONS ABOUT VENUS                                 |  | DESIGN REFERENCE MISSION                 |  |  |  |
|---|--|--|--|--|--|
|   |  | Orbiter                                  | Landers                                  | Balloons                                 | DRM with synergies                       |
| VENUS ATMOSPHERE  |  |  |  |  |  |
| How did Venus evolve to become so different from Earth?                     |  | Partial answer to the questions          | Major progress in answering the question | Will not answer the questions            | Major progress in answering the question |
| Was Venus ever habitable, and for how long?                                 |  | Will not answer the questions            | Fully addresses question                 | Fully addresses question                 | Fully addresses question                 |
| Did Venus lose a primary atmosphere due to impacts or loss to space?        |  | Major progress in answering the question | Fully addresses question                 | Fully addresses question                 | Fully addresses question                 |
| What drives Venus' atmospheric superrotation?                               |  | Major progress in answering the question | Partial answer to the questions          | Major progress in answering the question | Major progress in answering the question |
| How do geologic activity and chemical cycles affect the clouds and climate? |  | Partial answer to the questions          | Major progress in answering the question | Major progress in answering the question | Major progress in answering the question |
| How are atmospheric gases lost to space?                                    |  | Major progress in answering the question | Partial answer to the questions          | Major progress in answering the question | Major progress in answering the question |
|   |  | Fully addresses question                 | Major progress in answering the question | Partial answer to the questions          | Will not answer the questions            |



# Open Science Questions

## Geology

| MAJOR OPEN SCIENTIFIC QUESTIONS ABOUT VENUS                           |  | DESIGN REFERENCE MISSION                 |         |          |                    |
|---|--|--|---------|----------|--------------------|
|   |  | Orbiter                                  | Landers | Balloons | DRM with synergies |
| VENUS GEOLOGY   |  |  |         |          |                    |
| What is the volcanic and tectonic resurfacing history of Venus?       |  |  |         |          |                    |
| How were the heavily deformed highlands made?                         |  |  |         |          |                    |
| How active is Venus geologically?                                     |  |  |         |          |                    |
| Did Venus ever have plate tectonics and if so, when did it cease?     |  |  |         |          |                    |
| How are geology and climate connected on Venus?                       |  |  |         |          |                    |
| What has been the role of water and other volatiles in Venus geology? |  |  |         |          |                    |
|   |  |  |         |          |                    |
|   |  | Fully addresses question                 |         |          |                    |
|   |  | Major progress in answering the question |         |          |                    |
|   |  | Partial answer to the questions          |         |          |                    |
|   |  | Will not answer the questions            |         |          |                    |

# Open Science Questions

# Interior Structure

| MAJOR OPEN SCIENTIFIC QUESTIONS ABOUT VENUS                              |  | DESIGN REFERENCE MISSION                 |         |          |                    |
|--|--|--|---------|----------|--------------------|
|  |  | Orbiter                                  | Landers | Balloons | DRM with synergies |
| VENUS INTERIOR STRUCTURE   |  |  |         |          |                    |
| Does Venus have Earth-like continents?                                   |  |  |         |          |                    |
| What are the chemical, physical, and thermal conditions of the interior? |  |  |         |          |                    |
| How does mantle convection work on Venus?                                |  |  |         |          |                    |
| What is the size and physical state of the core?                         |  |  |         |          |                    |
| What is the structure of the Venus lithosphere?                          |  |  |         |          |                    |
| How have water and other volatiles affected Venus' interior evolution?   |  |  |         |          |                    |
|  |  | Fully addresses question                 |         |          |                    |
|  |  | Major progress in answering the question |         |          |                    |
|  |  | Partial answer to the questions          |         |          |                    |
|  |  | Will not answer the questions            |         |          |                    |

# Open Science Questions

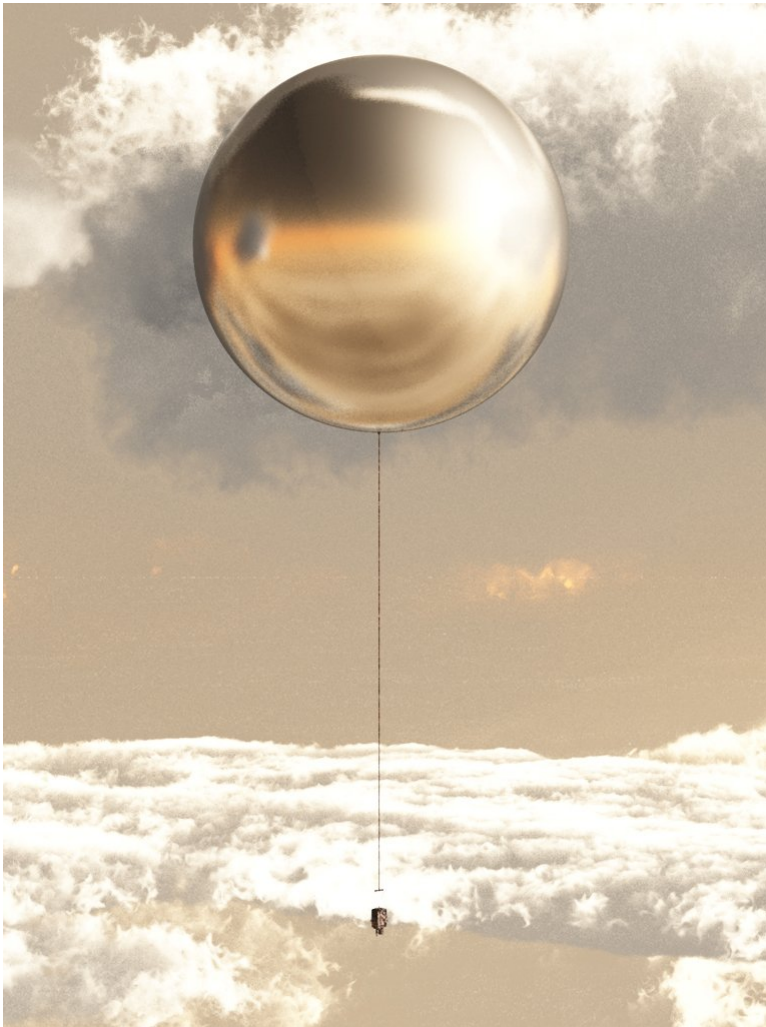
## Geochemistry

| MAJOR OPEN SCIENTIFIC QUESTIONS ABOUT VENUS                                 |  | DESIGN REFERENCE MISSION                 |         |          |                    |
|---|--|--|---------|----------|--------------------|
|   |  | Orbiter                                  | Landers | Balloons | DRM with synergies |
| VENUS GEOCHEMISTRY  |  |  |         |          |                    |
| Was there ever an ocean on Venus, and if so, when and how did it disappear? |  |  |         |          |                    |
| What caused the resurfacing of Venus over the past billion years?           |  |  |         |          |                    |
| What is the nature of chemical interactions between surface and atmosphere? |  |  |         |          |                    |
| What are the tectonic forces behind Venus' volcanism?                       |  |  |         |          |                    |
| How were the rocks and soils of Venus formed?                               |  |  |         |          |                    |
| What do chemical differences of terrains say about the evolution of Venus?  |  |  |         |          |                    |
|   |  |  |         |          |                    |
|   |  | Fully addresses question                 |         |          |                    |
|   |  | Major progress in answering the question |         |          |                    |
|   |  | Partial answer to the questions          |         |          |                    |
|   |  | Will not answer the questions            |         |          |                    |

# Venus Flagship In-Situ Science

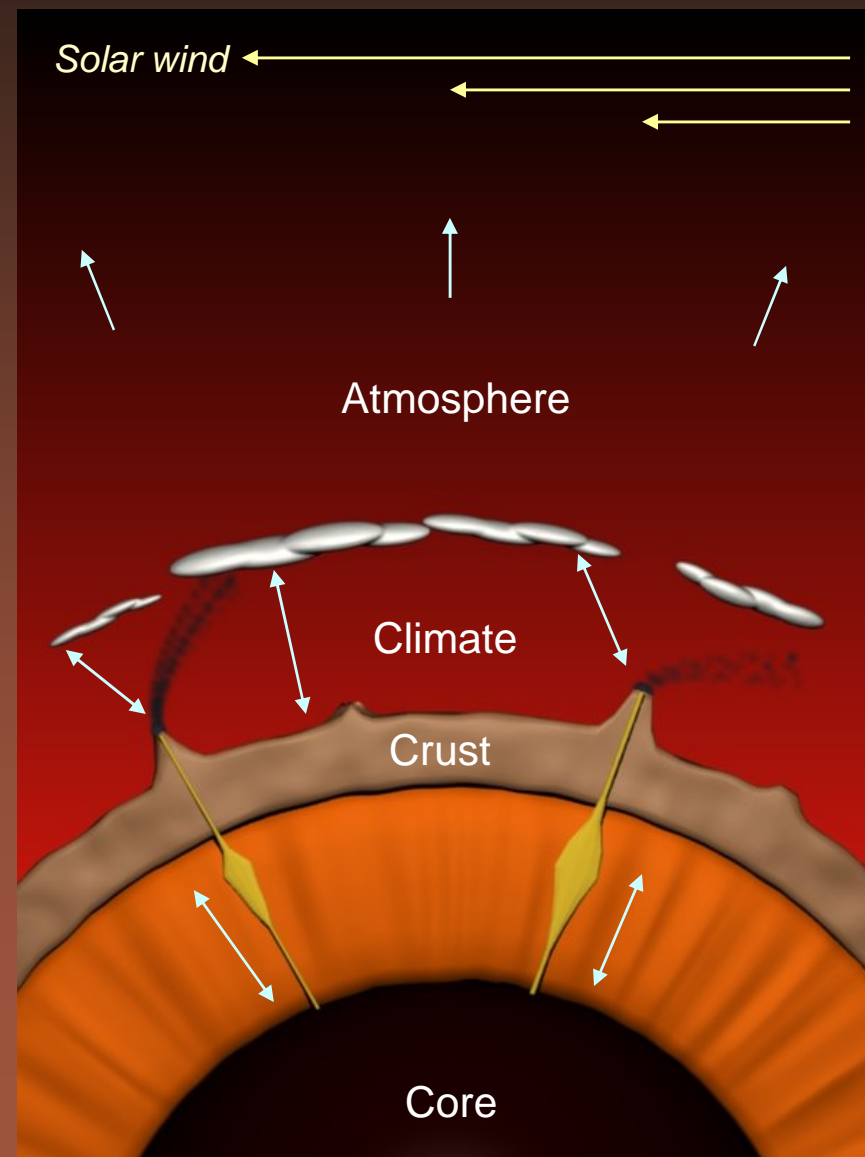
- Winds, cloud chemistry and microphysics
- Noble gases
- Radiative energy balance

- Elemental & mineralogical analysis of rocks & soils
- Descent & panoramic imaging
- Deep atmosphere composition
- Corner reflector, heat flux



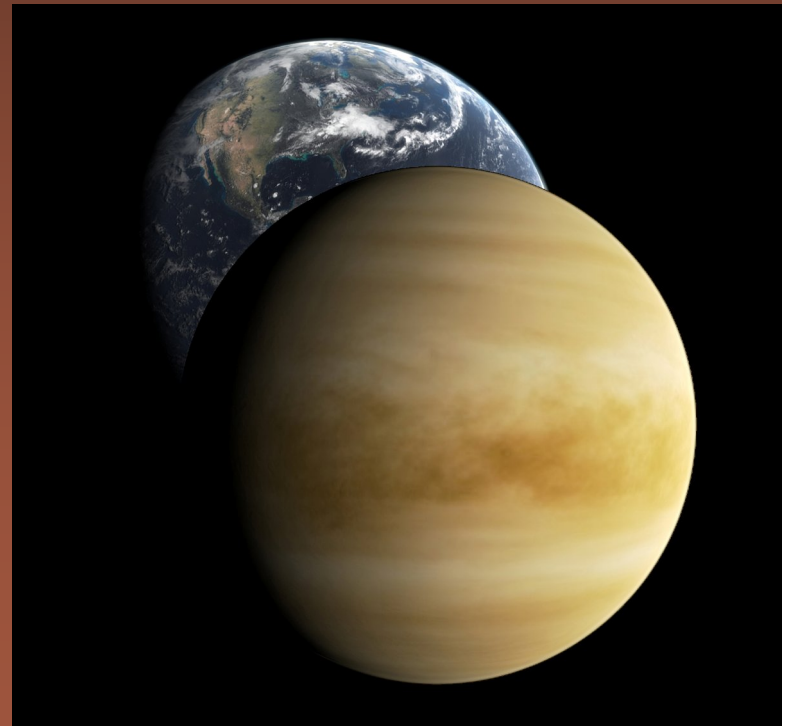
# STDT Summary

- What does the Venus greenhouse tell us about climate change?
  - Probes through atmosphere simultaneously with balloons
  - Chemistry of the surface
- How active is Venus?
  - Highly capable orbiter with high resolution radar imaging, topography, and temporal changes
  - Geothermal heat flux
  - Near-IR images
- When and where did the water go?
  - Geochemistry and mineralogy at 2 locations on Venus
  - Atmospheric isotopes for early evolution
- A Venus Flagship mission in 2020-2025 can be done with moderate technology investment and relatively low risk.



# Conclusions

- An orbiter, 2 balloons and 2 landers provide the highest science return.
- VFM studies Venus as an interconnected system – atmosphere, clouds, surface, and interior.
- VFM is a large NASA planetary mission with the explicit intention of better understanding our own world.







# Venus STDT Membership

Chairs: Mark Bullock (SwRI) and Dave Senske (JPL)

- **Atmosphere**

- **David Grinspoon** (DMNS)
- Anthony Colaprete (NASA Ames)
- Sanjay Limaye (U. Wisconsin)
- George Hashimoto (Japan)
- Dimitri Titov (ESA)
- Eric Chassefiere (France)
- Hakan Svedhem (ESA)

- **Geochemistry**

- **Allan Treiman** (LPI)
- Steve Mackwell (LPI)
- Natasha Johnson (NASA))

- **Geology and Geophysics**

- **Dave Senske** (JPL)
- Jim Head (Brown University)
- Bruce Campbell (Smithsonian)
- Gerald Schubert (UCLA)
- Walter Kiefer (LPI)
- Lori Glaze (GSFC)

- **Technology**

- **Elizabeth Kolawa** (JPL)
- Viktor Kerzhanovich (JPL)
- Gary Hunter (GRC)
- Steve Gorevan (HoneyBee)

- **Ex Officio**

- Ellen Stofan (VEXAG Chair)
- Tibor Kremic (NASA)

## JPL Venus Flagship Mission Architecture Study

**Study Lead:** **Jeff Hall**

Tibor Balint  
Craig Peterson  
Alexis Benz  
Team X

## NASA and JPL

Jim Cutts (JPL)  
Adriana Ocampo (NASA HQ)